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MEASUREMENTS ON WING-TIP BLOWING

BY

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ABSTRACT

The aerodynamics of a rectangular wing with a jet exhausting in the spanwise direction from the tips has been explored experimentally. By effectively changing the span of the wing as well as outwardly displacing the tip vortices, such jets can induce aerodynamic forces that could be used for roll and lateral control of aircraft. The concept has been investigated for a variety of jet intensities, angles of attack, and aspect ratios. The results appear to confirm theoretically predicted scaling laws for lift gain and moment generation due to blowing.

NOMENCLATURE

A	wing aspect ratio
b	wing semi-span
c	wing chord
C_μ	jet momentum coefficient
C_l	rolling moment coefficient
$\bar{C}_l$	measure of the rolling moment coefficient
C_L	lift coefficient
C_{L_o}	lift coefficient for zero blowing
d	tip vortex outward excursion
h	slot width
q_∞	free stream dynamic pressure
U_∞	free stream velocity
α	angle of attack
δ_e	equivalent aileron deflection
ΔC_L	lift coefficient increment due to blowing
Δp	difference between plenum and static pressures

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1. INTRODUCTION

A thin jet of fluid exhausting in the spanwise direction from a wing tip, and roughly aligned with the chord will affect the forces acting on the wing by modifying the effective aspect ratio of the wing. To some extent the jet behaves as an extension of the wing; it can support a finite pressure difference between its two sides in the vicinity of the tip, which is reflected in a curvature of the jet sheet and a spanwise displacement of the tip vortex. Modification of both the net lift and the rolling moment of the wing may be obtained by modulation of jet strength in the absence of any moving surfaces. Wing tip blowing could therefore be considered as advantageous to augment wing lift or to provide control response in flight regimes where conventional systems would be ineffective, e.g. stalled flight. Tailoring of the jet parameters (slot length, position and efflux angle) may also have a positive effect on stability derivatives (yaw due to roll etc.) and aeroelastic interactions such as control reversal, associated with high aspect ratio wings.

The intent of this research program was to investigate the relative importance of each of the parameters and to obtain a fundamental understanding of the fluid phenomena and their relative merits. The results reported here correspond to systematic variations in jet intensity, aspect ratio and angle of attack. Ongoing work includes parametric investigation of jet exit configuration, jet exit angle, and jet location.

A symmetrical NACA 0018 airfoil section was chosen and the model dimensions fixed to produce a maximum aspect ratio of 3.1, which could then be varied by sliding a splitter plate along the wing span.

The following chapters of this report cover the experimental apparatus and techniques, a compilation of the data obtained and an initial discussion of the important phenomena.

Since previous work on this concept emphasized its application to lift augmentation, as opposed to roll or lateral control, it dealt with blowing intensities considerably larger than were investigated here. Ayers and Wilde[1] reported measurements on a wing of aspect ratio 1.39 and 50 degrees of sweep, showing significant gains in lift with lateral blowing, as well as beneficial effects of blowing on stall. Carafoli[2] conducted experiments with a straight wing of aspect ratio 2, and attempted a theoretical formulation with limited success. Later, Carafoli and Camaracescu[3] reported experiments on small aspect ratio wings, observing that lift augmentation due to wing tip blowing was greater for smaller aspect ratios. Further experimental work was conducted by White[4], who noticed that beneficial effects on drag were possible. Briggs and Schwind[5] considered this concept as a lift augmentation device for STOL aircraft. Their experiments suggest that a net gain in STOL capabilities would be possible. Hickey[6] tested swept wings of aspect ratios 1.9 and 2.5 and observed that the rate of gain of additional lift was greater for weaker blowing. Wu et al[7,8] studied the concept

of tip blowing where several discrete, thin jets ejected from wing tips, and inferred similarities with the winglet concept. Tavella and Roberts[9] developed a theory for the concept of lateral blowing, and obtained scaling laws valid for weak blowing.

2. EXPERIMENTAL APPARATUS AND TECHNIQUES

2.1 Low Speed Wind Tunnel

The Stanford low speed wind tunnel has a 18" by 18" test section with a length of 32". It is a continuous operation, closed-loop facility driven by a variable pitch fan. Speed control is achieved by remote adjustment of the blade pitch and a maximum centerline free stream speed of $57 ms^{-1}$ is obtainable. Calibration and setting of the tunnel is by observation of a reference pressure difference across the contraction, the two reference locations being sufficiently removed from the test section to avoid model interference.

2.2 Wind Tunnel Model

The requirements for the model were symmetry about the chordline, simplicity of construction, modest aspect ratio, and minimum jet interference with the wind tunnel walls. The final design was fixed as a NACA 0018 airfoil section with a chord of 15cm and a span, not including the tip piece, of 22.6cm. The basic aspect ratio of the wing model was 3.1. This thick section was chosen to facilitate the incorporation of both a plenum duct and a large number of pressure tappings. Initial scalings of the mass flow requirements and expected translations of the tip vortex suggested that a slot height of 0.15cm would be suitable. The slot was positioned in the plane of symmetry, over 73% of the chord and exiting in the spanwise direction with no deflection.

The tip shape was chosen to be given by a diameter distribution equal to the wing thickness distribution. The resulting planform and overall dimensions are shown as Fig. 1. The model was mounted on a 20.3cm diameter circular disc which was flush mounted into the tunnel floor and which could be manually rotated to provide incidence adjustment. An additional circular splitter plate which could slide along the span of the wing was manufactured. This enabled measurement of the effects of varying aspect ratio upon the effectiveness of lateral blowing.

A total of 192 surface pressure tappings, divided equally between 8 spanwise stations, were installed in the model. At each station the pressure tappings were divided equally between the upper and lower surface. An additional tapping was provided in the model plenum to assess the blowing pressure.

An existing high pressure air supply capable of providing a maximum of $0.25 \mathrm{Kgsec}^{-1}$ of mass flow was used for the tip jet blowing. The mass flow was measured using a Venturi type mass flow meter and correlated with estimates obtained from the measurements of the internal duct pressure.

2.3 Data Acquisition

The 192 pressure tappings in the wing were connected to a 4-barrel "J" series Scanivalve module with 48 ports per barrel. The Scanivalve was automatically stepped and the data acquired by a PDP 11/23 minicomputer, enabling a full spanwise load distribution to be recorded by a single pass of the Scanivalve.

Each individual Scanivalve pressure was obtained as the average of 30 samples at a frequency of approximately 1KHz. The data was reduced to pressure coefficients, section lift coefficient, and overall load and rolling moment coefficient, and stored for future reference. On-line graphical display of local pressure distributions and global results was available. In this manner a wide variety of conditions could be examined in a short space of time.

A five-hole pitot probe was also used to measure the flow vectors downstream of the wing tip. Flow angles of up to 45 degrees could be measured using the probe, which was connected to a computer-controlled, 3-axis traversing gear. Cross flow velocity vectors on planes normal to the free stream could be measured downstream of the wing.

3. RESULTS

This initial study was formulated to provide information regarding the fundamental aspects of wing-tip blowing. As such a test matrix was constructed to sequentially vary jet strength, angle of attack, and aspect ratio.
The blowing strength is characterized by the jet momentum coefficient, which is here defined as

$$C_\mu = 2\frac{h}{c}\frac{\Delta p}{q_\infty} \tag{1}$$

where Δp is the difference between the total pressure of the jet and the static pressure in the environment where it discharges. Here Δp is considered to be equal to the gage pressure in the plenum, since tunnel static pressure was very close to atmospheric. Results in Figs. 2 through 19 correspond to model aspect ratio set to its basic value 3.1.

Fig. 2 shows the velocity field on a plane normal to the free stream, one chord behind the wing trailing edge, as obtained with the five-hole probe.

Fig. 3 shows the trajectory of the wing-tip vortex core on a plane normal to the free-stream.

Fig. 4 shows the horizontal displacement of the vortex position as blowing is applied.

Figs. 6 to 9 show isobar contours for the upper and lower surfaces, for selected angles of attack and blowing intensities.

Fig. 10 depicts a three dimensional view of the load distribution on upper and lower surfaces with and without blowing.

Fig. 11 shows the lift coefficient as a function of angle of attack, parametrically in blowing intensity.

Fig. 12 shows the lift increment as a function of angle of attack and parametrically in blowing intensity.

Figs. 13 and 14 repeat the same data as function of blowing intensity, parametrically in angle of attack.

Fig. 15 and 16 show the relative lift gain as function of angle of attack and blowing intensity.

Fig. 17 shows the same data plotted against the ratio of blowing intensity to angle of attack.

Fig. 18 shows a measure of the rolling moment coefficient that would result from one-sided blowing in the case of a full-span wing. The rolling moment coefficient is defined as

$$C_l = \frac{\text{rolling moment}}{\text{span } q_\infty \text{ wing area}} \tag{2}$$

The measure of the rolling moment coefficient reported here is computed as follows:

$$\bar{C}_l = \frac{1}{4}\int_o^1 \triangle C_L d\left(\frac{y}{b}\right) \tag{3}$$

These two quantities are not identical since in the full-span case one-sided blowing affects the loading along the entire span of the wing. However, a theoretical study[9] indicated that

they are related through a factor close to unity.

Fig. 19 shows the effective deflection of conventional ailerons, covering 25% of the chord and 25% and 50% of the semi-span, needed to produce the same rolling moment as measured in the half-span model. The information on rolling moment produced by conventional ailerons was taken from reference[10], where measurements on a wing model of the same planform as the one of interest here were reported.

Fig. 20 shows the effect of varying the aspect ratio on the lift gain, for selected values of blowing intensity and angle of attack.

It is estimated that the general degree of accuracy on globally derived results is better than ± 5%. This takes into account variations in tunnel speed, blowing rate, transducer calibration, inaccuracies in the setting of the angle of attack, and the resolution of the A/D converter presently in use.

In all the presented results, even for the totally symmetrical case presently under investigation, a gain in the lift coefficient is apparent as tip blowing is applied. Results for 0 degree angle of attack are not shown since the wing must have finite lift to indicate meaningful results.

4. DISCUSSION

The global mechanism responsible for the lift gain due to blowing is best observed by studying the features of the wake behind the wing. Fig. 2 shows the wake structure at a distance of one chord behind the trailing edge, as mapped with the five-hole probe. As shown in Fig. 3, the tip vortex moves upwards and outwards as blowing is applied. It is known that the asymptotic position of the vortex core far downstream is related to the wing span through a weak function of aspect ratio[11] (a constant for elliptical wings). Hence, the outward movement of the vortex core indicates an effective change of the wing aspect ratio as a function of blowing, suggesting that to some extent the jet behaves as a fluid extension of the wing, supporting a pressure difference between its surfaces. Fig. 4 shows that the outward distance that the vortex moves is a non-linear function of blowing intensity. From these figures it can be concluded that the jet curls up and merges with the tip vortex. A plausible three-dimensional view is sketched in Fig. 5.

The source of lift gain can be identified in greater detail by analyzing the isobar patterns shown in Figs. 6 to 9. Over most of the upper surface, blowing causes a general shift of the isobars towards the trailing edge indicating increased suction, except in a small region near the corner of the trailing edge and the tip, where suction decreases. The increase in suction is more marked near the tip and on the rear two-thirds of the

chord. The lower surface shows a less complex situation; there is a fairly uniform gain in the pressure excess. Fig. 10 shows how blowing affects the load distribution on the upper and lower surfaces. Over most of the upper surface the pressure changes by an almost uniform value, except near the tip, where three regions can be distinguished. Close to the leading edge, suction is slightly decreased. This is probably due to the effective contouring imposed by the jet on the wing planform. A larger portion of the region near the tip is subjected to a significant increase in suction. This added suction denotes an acceleration of the fluid due to entrainment into the jet and velocity induced by the rolled up tip vortex, indicating the presence of both viscous and inviscid mechanisms. The decreased suction in the small region near the trailing edge is probably due to the removal, by blowing, of the tip vortex which had established itself above that area of the wing before blowing was applied.

On examination of the load distribution on the lower surface we see that the increase in pressure is more pronounced near the tip. Since viscous entrainment into the jet is also expected to be present on its lower surface, and would tend to accelerate the flow, the observed deceleration suggests that the inviscid effect of span increase is more important than the effect of viscous entrainment for a symmetrical arrangement of the slot. The main source of lift is the redistribution of downwash along the span, causing a change in the effective angle of attack. This confirms the previous statement, that lateral blowing effec-

tively changes the wing aspect ratio. With regard to the effect of the aerodynamic twist imparted to the wing by the curled-up jet, it appears to be localized near the tip and of minor importance relative to the total lift coefficient. However, this phenomenon might be of some significance in connection with the rolling moment, where the importance of pressure changes near the tip are amplified.

Figs. 11 and 12 reveal that the increment of lift due to lateral blowing is a non-linear function of angle of attack. A change in angle of attack at fixed blowing rate causes the wing aspect ratio to change, modifying the loading at the tip, which in turn affects the aspect ratio. The combined effect of these changes suggest that the lift slope will be singular about the value of angle of attack for zero lift. Figs. 13 and 14 also show a non-linear dependence of lift gain vs blowing rate. This non-linearity can also be explained in terms of simultaneous changes affecting each other; an increment of the blowing rate causes a change in the loading of the wing near the tip, and this affects the length that the jet projects into the free stream. This explanation would suggest that the singular behavior occurs about $C_\mu = 0$.

The relative increment of lift coefficient for a set blowing intensity becomes larger for smaller angles of attack, confirming the non-linear way the lift increment approaches zero. When the data points in Figs. 15 and 16 are combined in the form presented in Fig. 17, they collapse on a single line closely

described by the ratio of blowing intensity to angle of attack raised to a suitable power which appears to be close to 0.7. In a theoretical discussion[9], this exponent is shown to be 2/3. In Fig. 17 the data points corresponding to angle of attack of 2 degrees fail to collapse, this was due to an error in the angle of attack setting for that particular case.

The rolling moment due to one-sided lateral blowing is discussed in terms of the quantity $\tilde{C}_l$ as shown in Fig. 18 . This quantity, called "measure of the rolling moment coefficient", also exhibits non-linear dependence on blowing intensity and angle of attack. The considerably more scatter in Fig. 18 is probably due to magnification of experimental uncertainties near the tip. In order to evaluate the potential of this concept as a means of generating rolling moments, the deflections for two different conventional aileron configurations, required to produce the same rolling moment (for this purpose it is assumed $C_l = \tilde{C}_l$), are shown in Fig. 19. The ailerons are on wings of identical planform to that presently under consideration, cover 25% of the chord and extend over 25% and 50% of the semi-span respectively[10]. The moments produced by the deflection of only one of the ailerons in the full-wing was used to compute the deflection angles in Fig. 19.

Finally, the effect of aspect ratio on lift increment was investigated. This was done by placing a movable splitter plate over the wing section, and simulating different wing spans by different plate positions. The results for selected values

of angle of attack and blowing intensity are summarized in Fig. 20. We see that the lift increments become larger for smaller aspect ratios. In fact, it is expected that the lift gain would become unbounded for infinitely small aspect ratio. This is a consequence of a relative change in span for constant blowing strength becoming ever more significant as the aspect ratio decreases.

5. CONCLUSIONS AND RECOMMENDATIONS

The experiments have shown that tip blowing can be utilized as a means of producing changes in the wing loading, leading to augmentation in lift and the generation of rolling moments. In cases where there is interest in small forces and moments, such as in roll and lateral control, tip blowing of small and moderate intensity appear promising.

The way this concept generates forces differs from conventional flaps or ailerons primarily in two respects:

- The forces and moments are non-linear functions of angle of attack and blowing intensity. This will have a bearing on the dynamic behavior of the aircraft.
- The forces are produced by an effective change in the span of the wing, as opposed to a change in the wing camber, which is the case in conventional ailerons or flaps. This causes the forces generated by tip blowing to be distributed over the entire span of the wing.

With regard to the rolling moment, experiments conducted with half-span models can only provide an estimate of the effects of one-sided blowing on a full-span wing. Further work in this area should aim at establishing a more exact relationship between the rolling moment produced by tip blowing, and the "measure of rolling moment", reported here.

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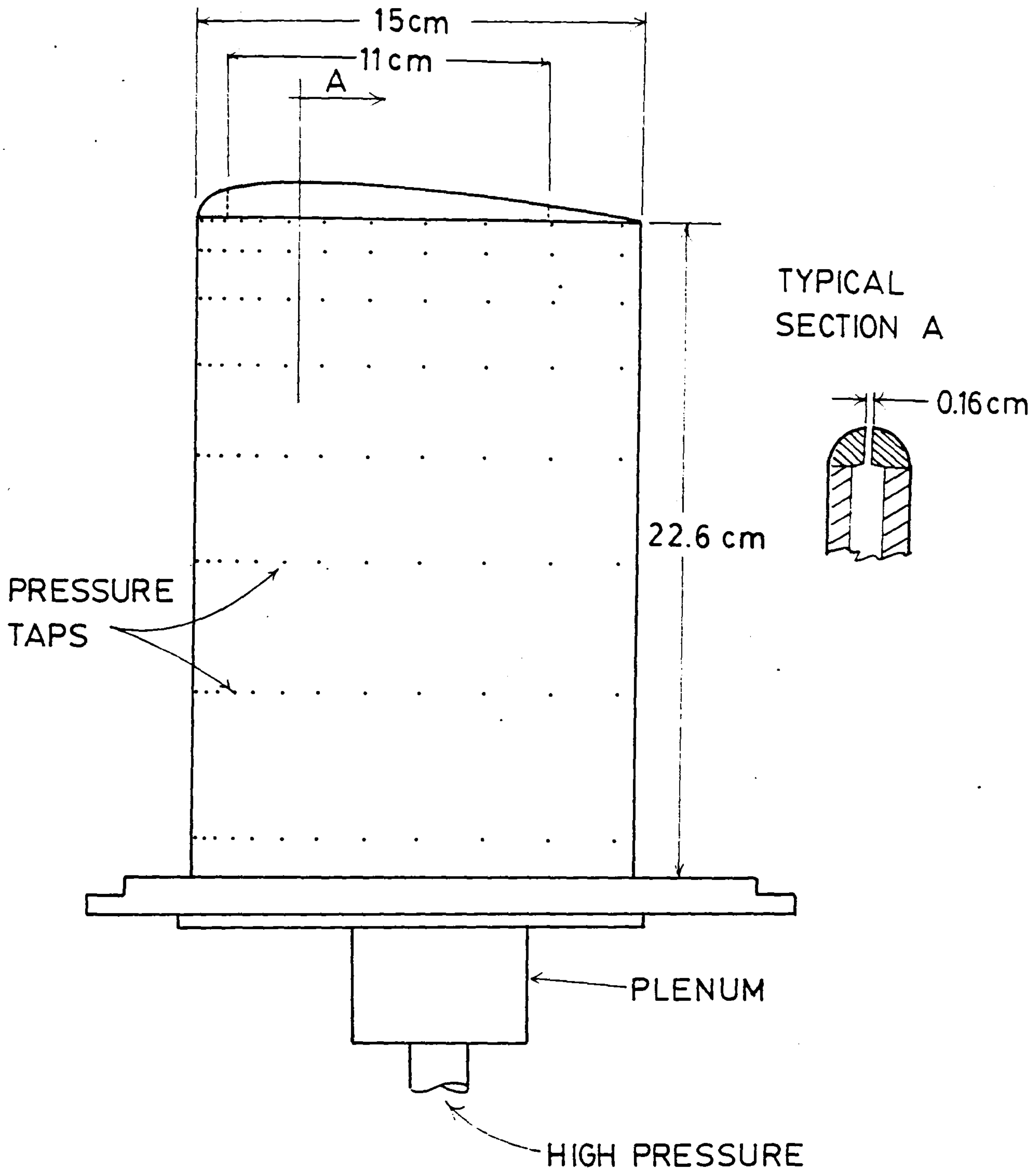

Fig. 1 Wing model.

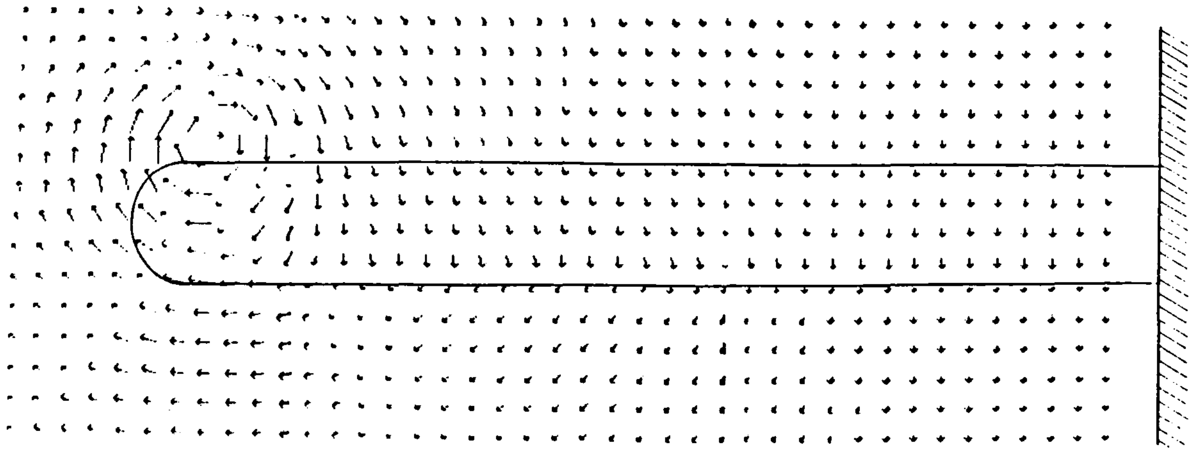

Fig. 2 Velocity field on cross-flow plane one chord behind wing trailing edge.
$\alpha = 6°, C_\mu = 0.04.$

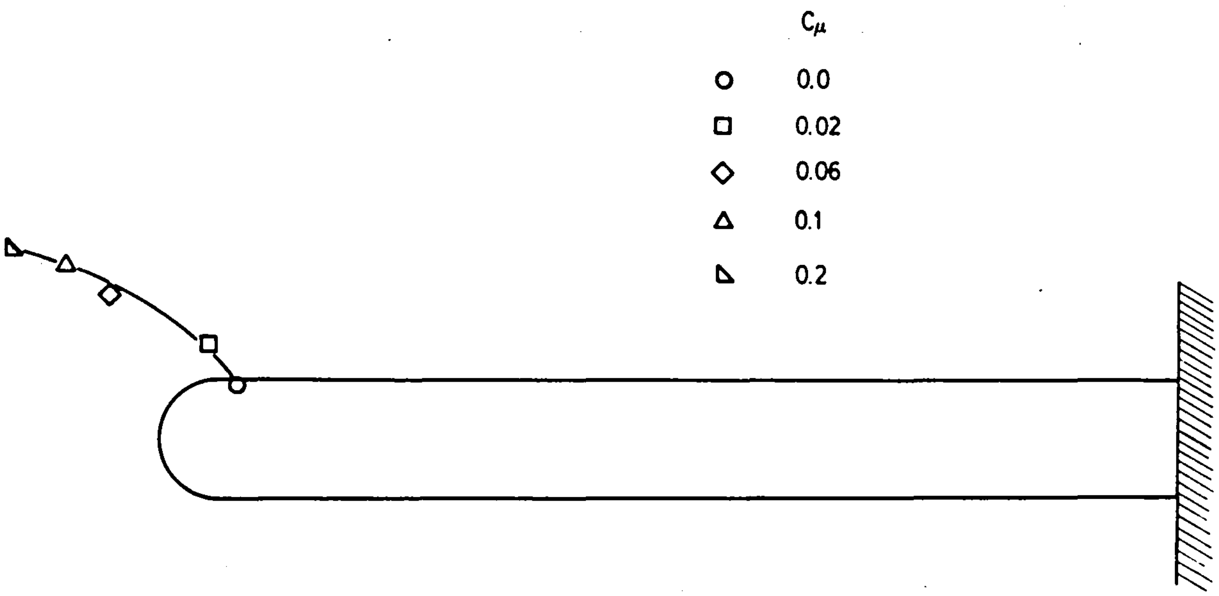

Fig. 3 Loci of wing-tip vortex core on cross-flow plane one chord behind trailing edge.
$\alpha = 2°.$

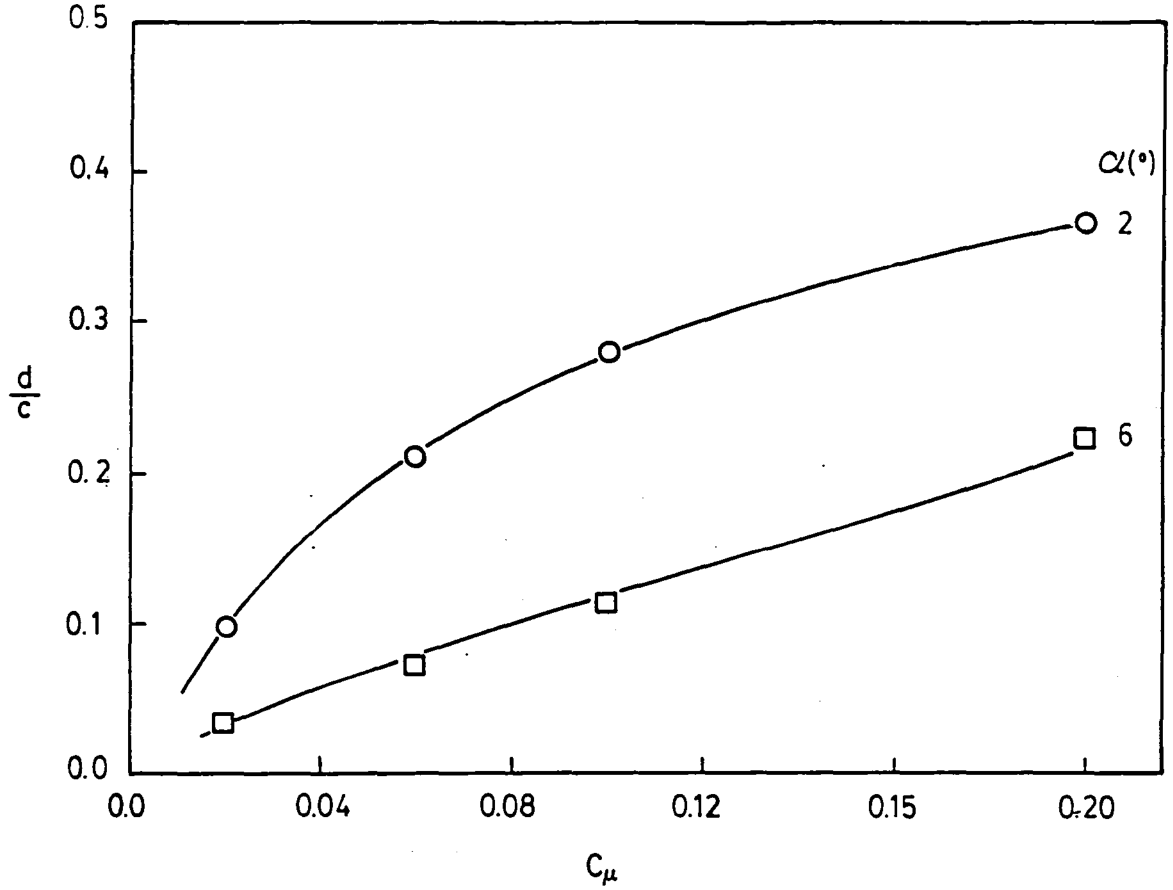

Fig. 4 Horizontal displacement of wing-tip vortex core, measured at one chord behind trailing edge.

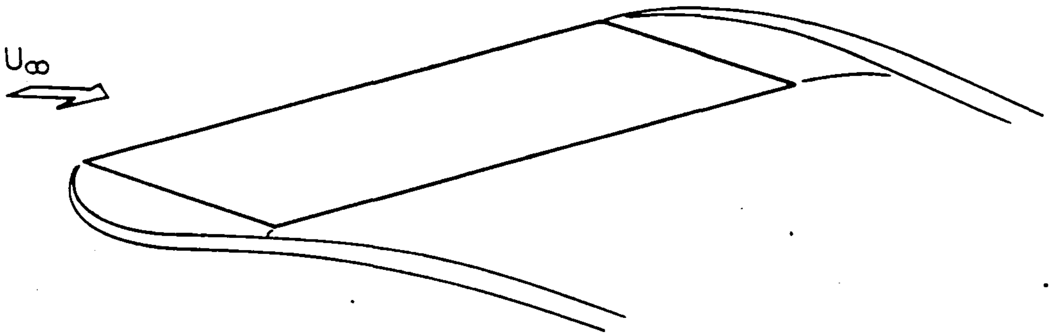

Fig. 5 Wing-tip jet roll-up.

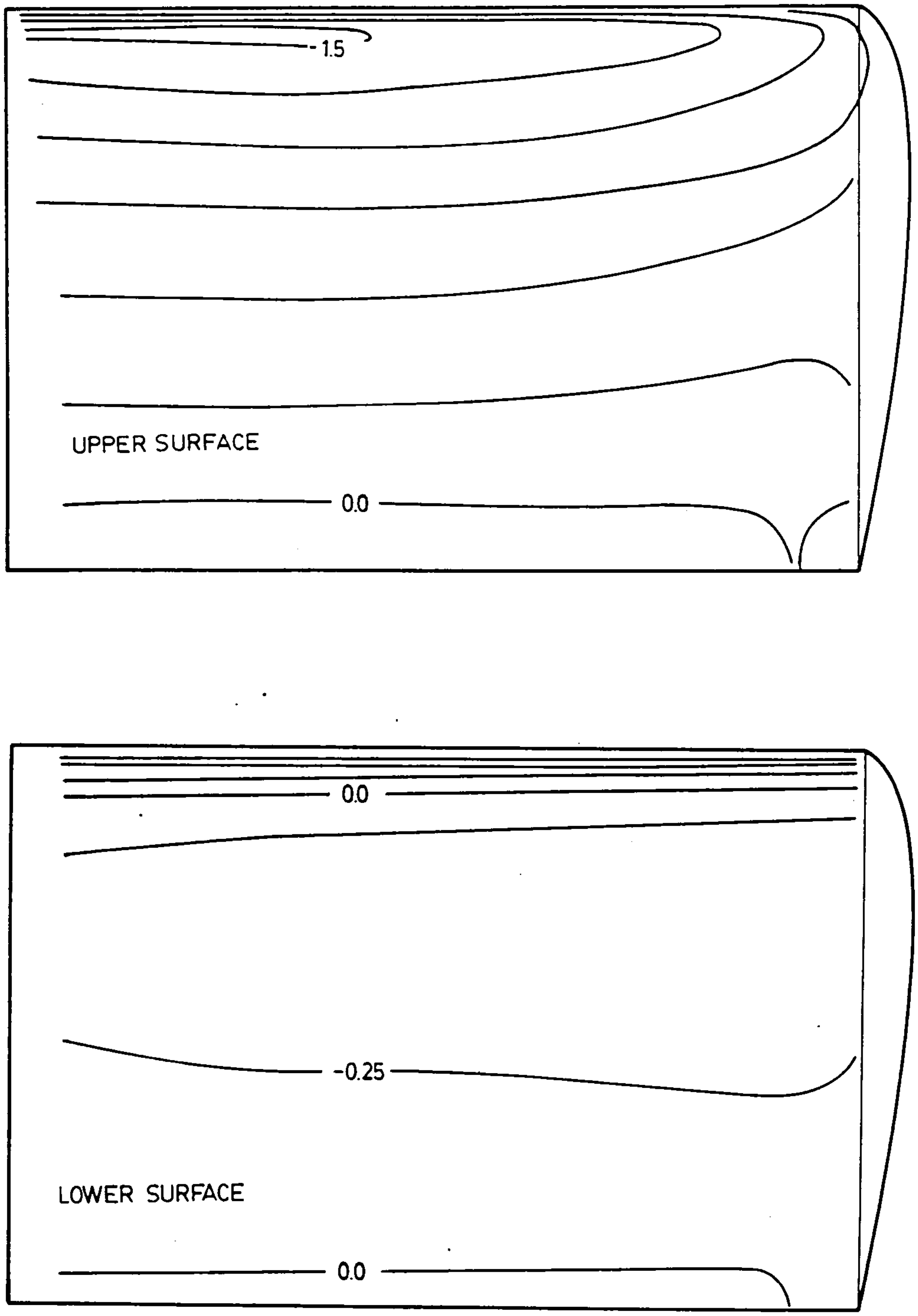

Fig. 6 Isobar contours.
Spacing between contours $\Delta C_p = 0.25$,
$\alpha = 6°$, $C_\mu = 0.0$.

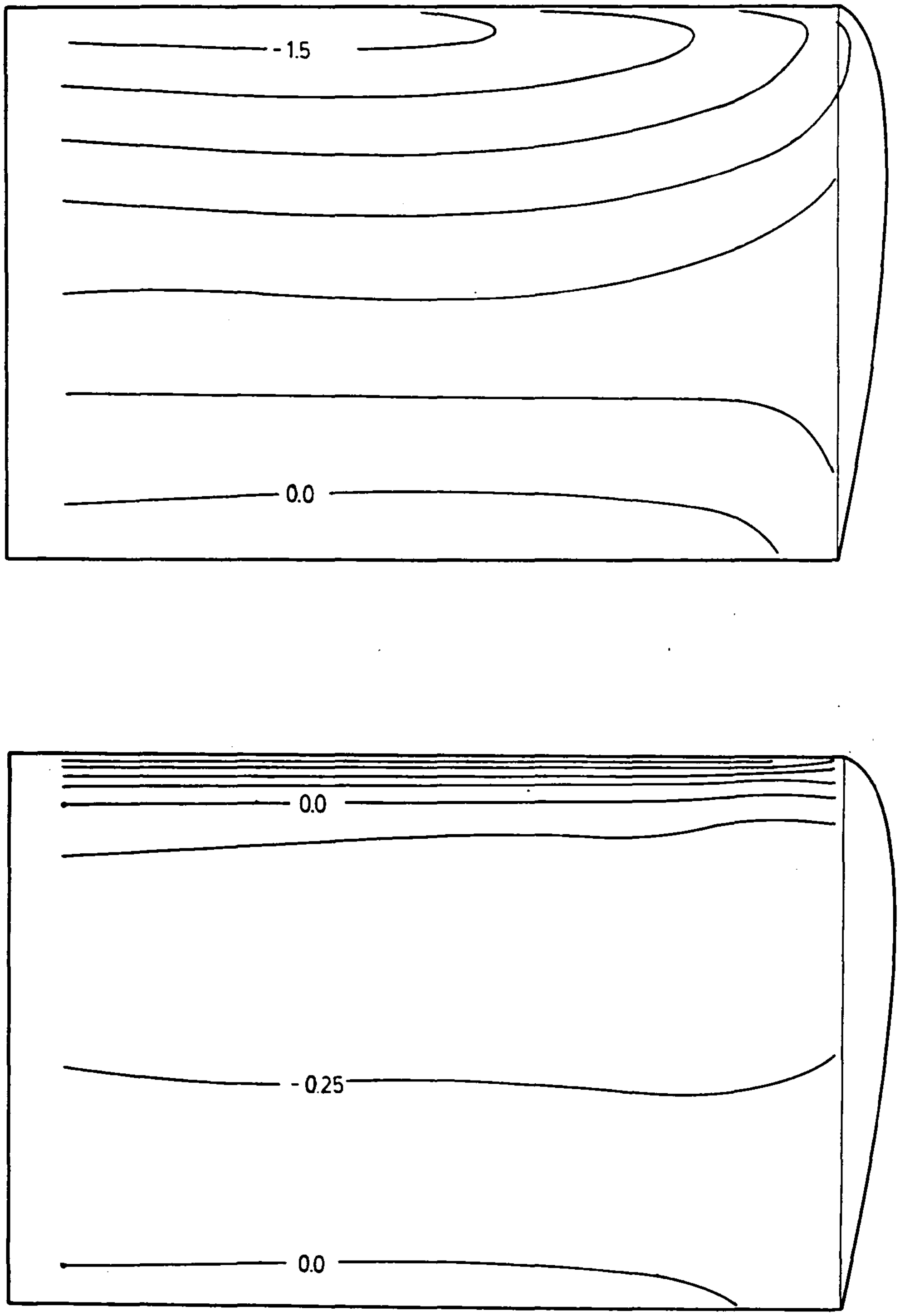

Fig. 7 Isobar contours.

$\alpha = 6^{\circ}, C_{\mu} = 0.04.$

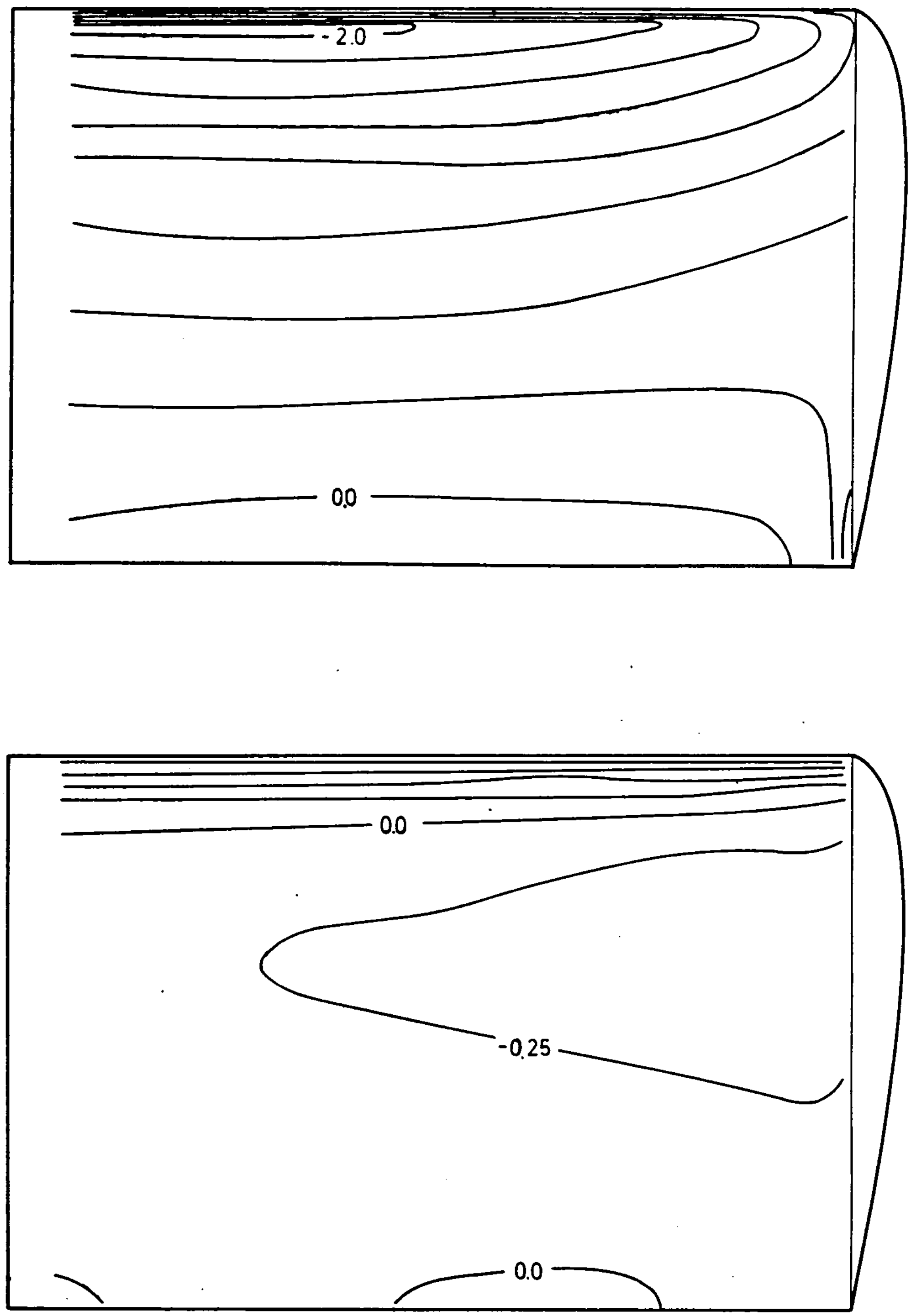

Fig. 8 Isobar contours.
$\alpha = 8^\circ$, $C_\mu = 0.0$.

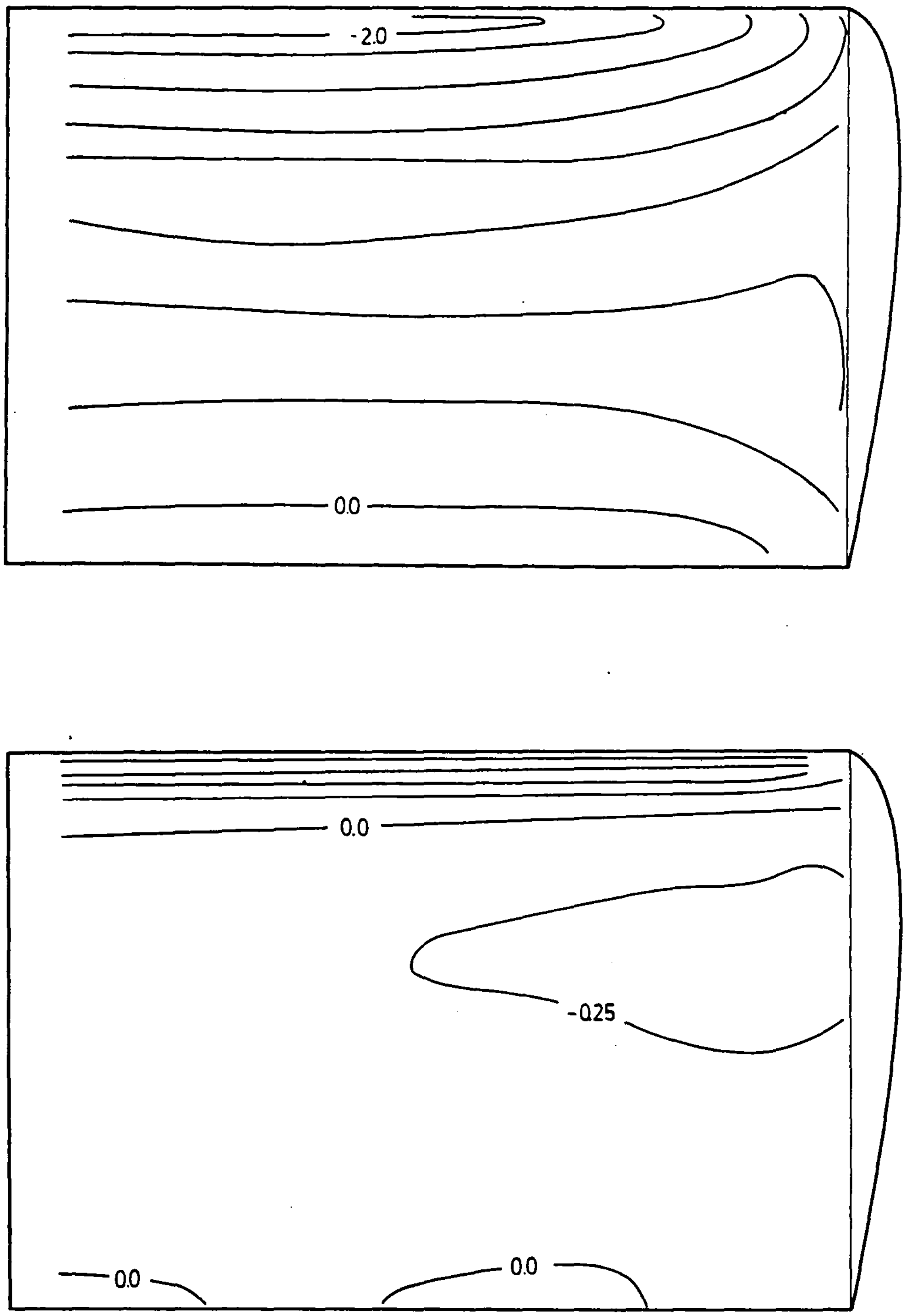

Fig. 9 Isobar contours.
$\alpha = 8^\circ$, $C_\mu = 0.1$.

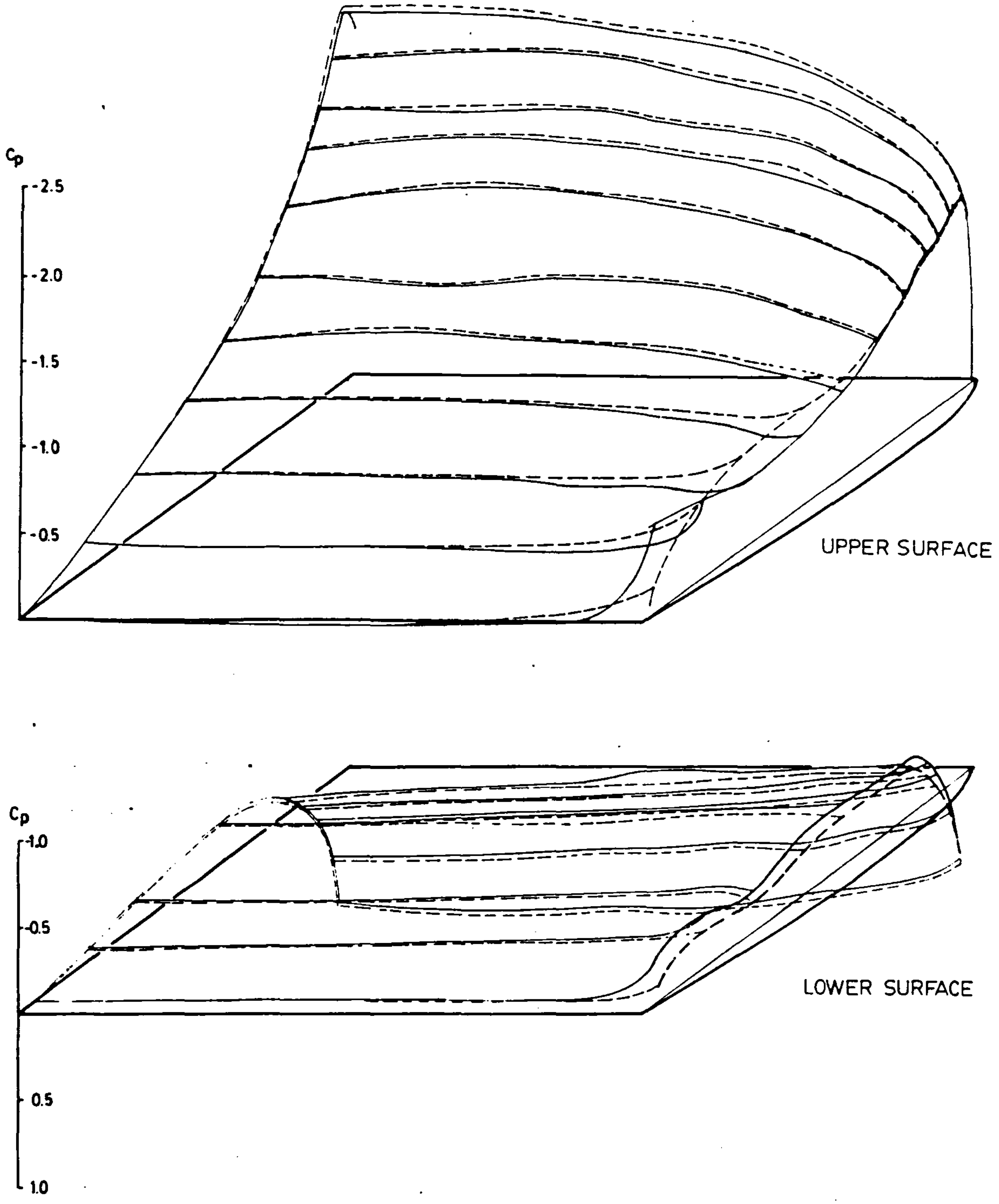

Fig. 10 Wing load distributions.
—— $C_\mu = 0.0$, - - - $C_\mu = 0.1$.

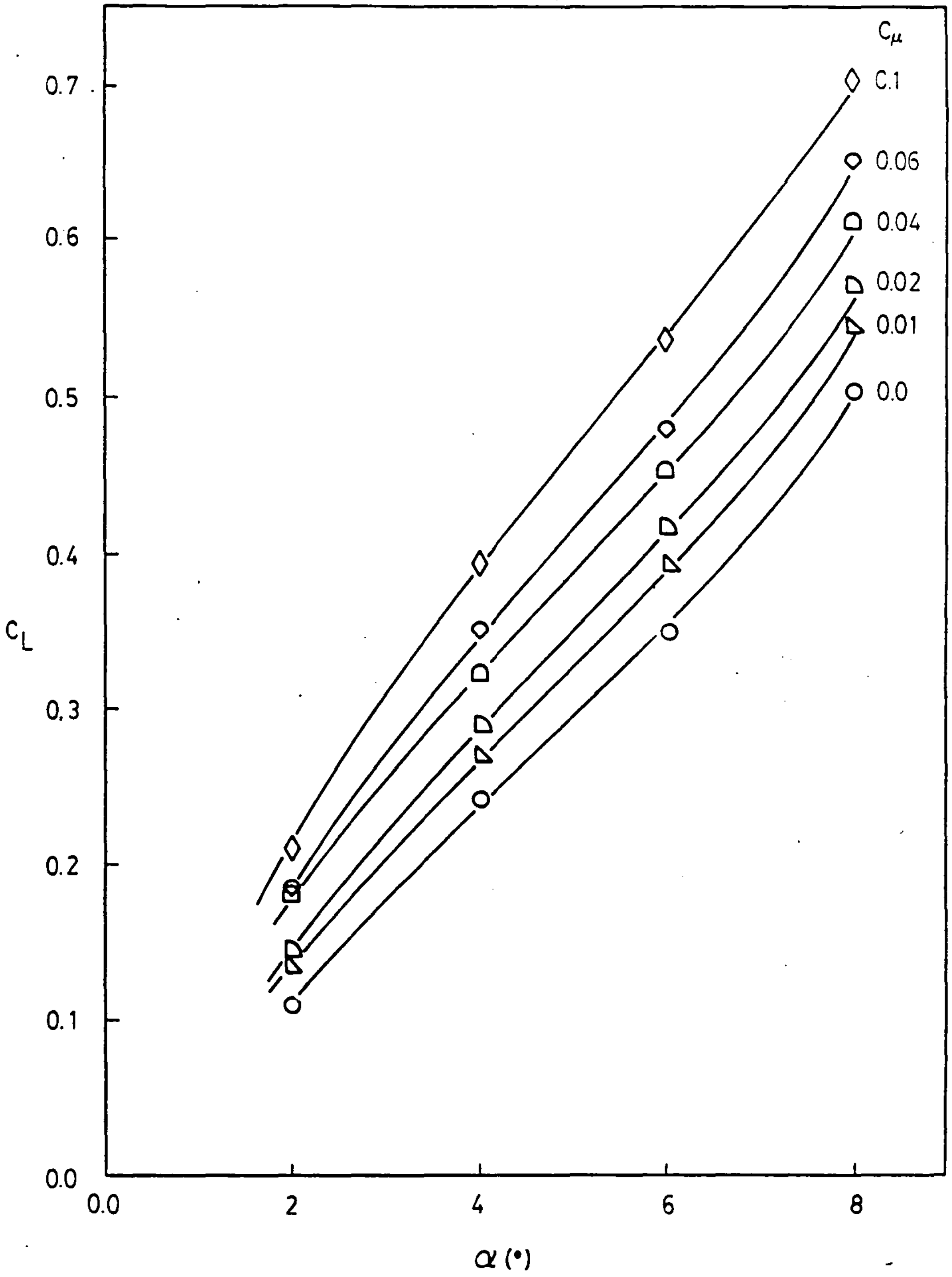

Fig. 11 Effect of angle of attack on lift coefficient for different blowing intensities.

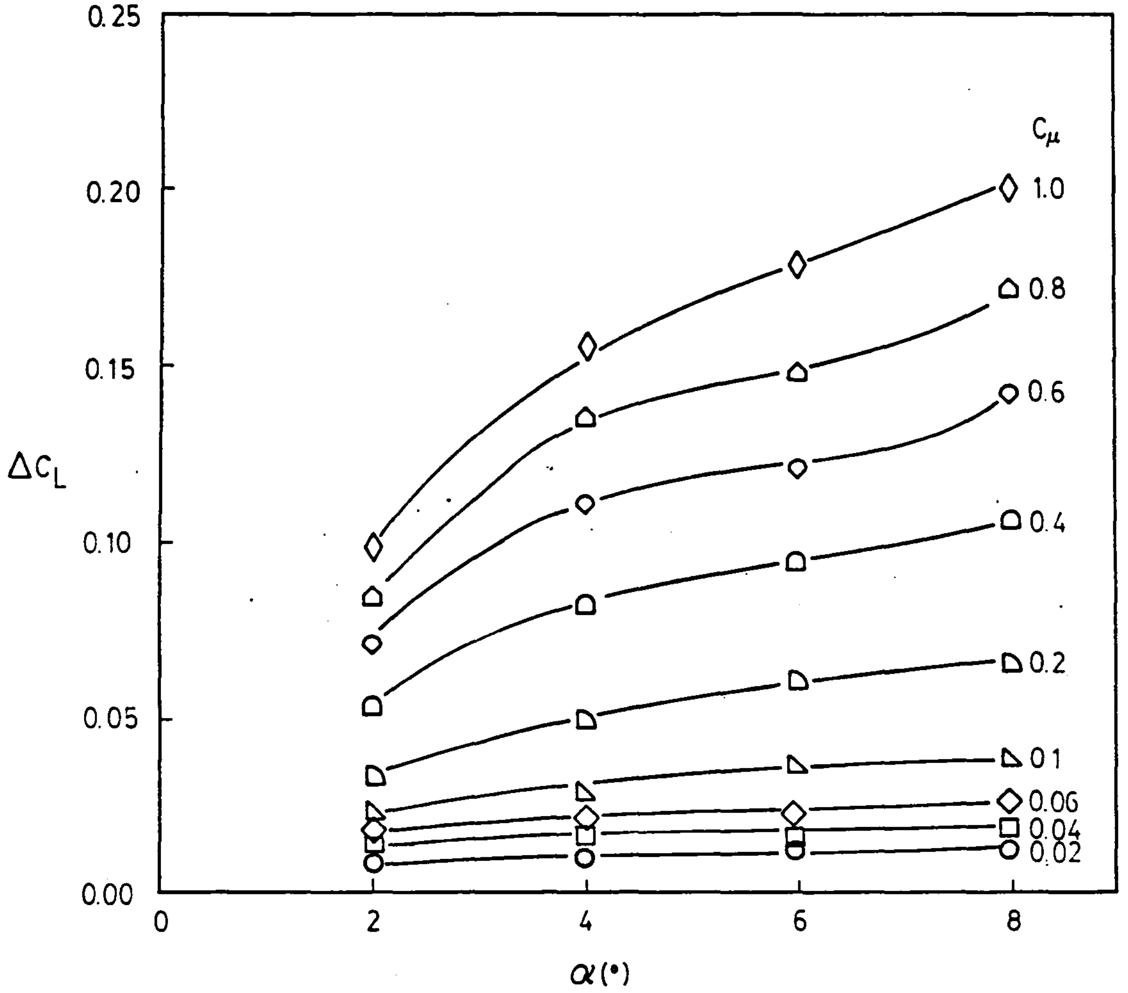

Fig. 12 Lift increment as function of angle of attack.

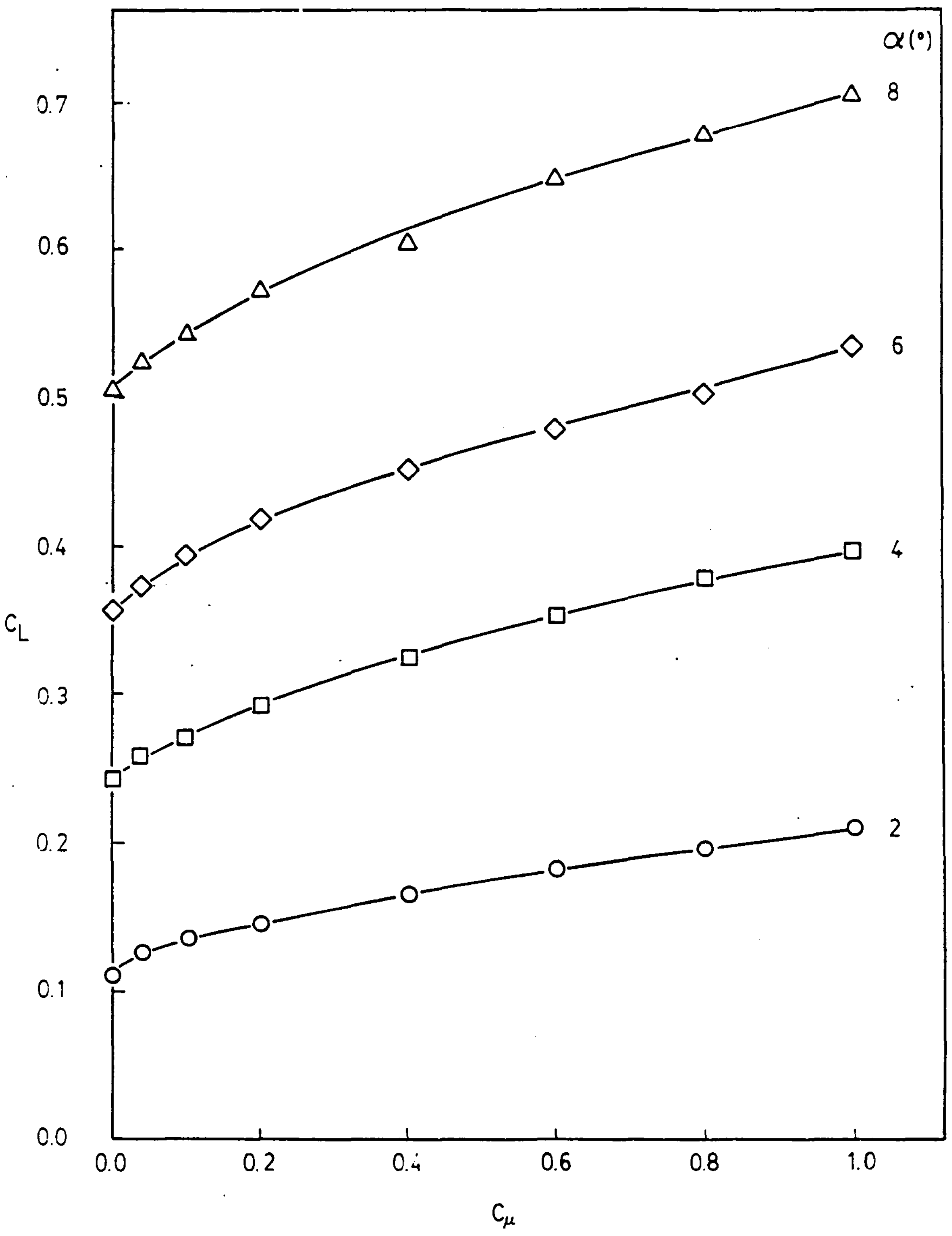

Fig. 13 Effect of blowing on lift coefficient for different angles of attack.

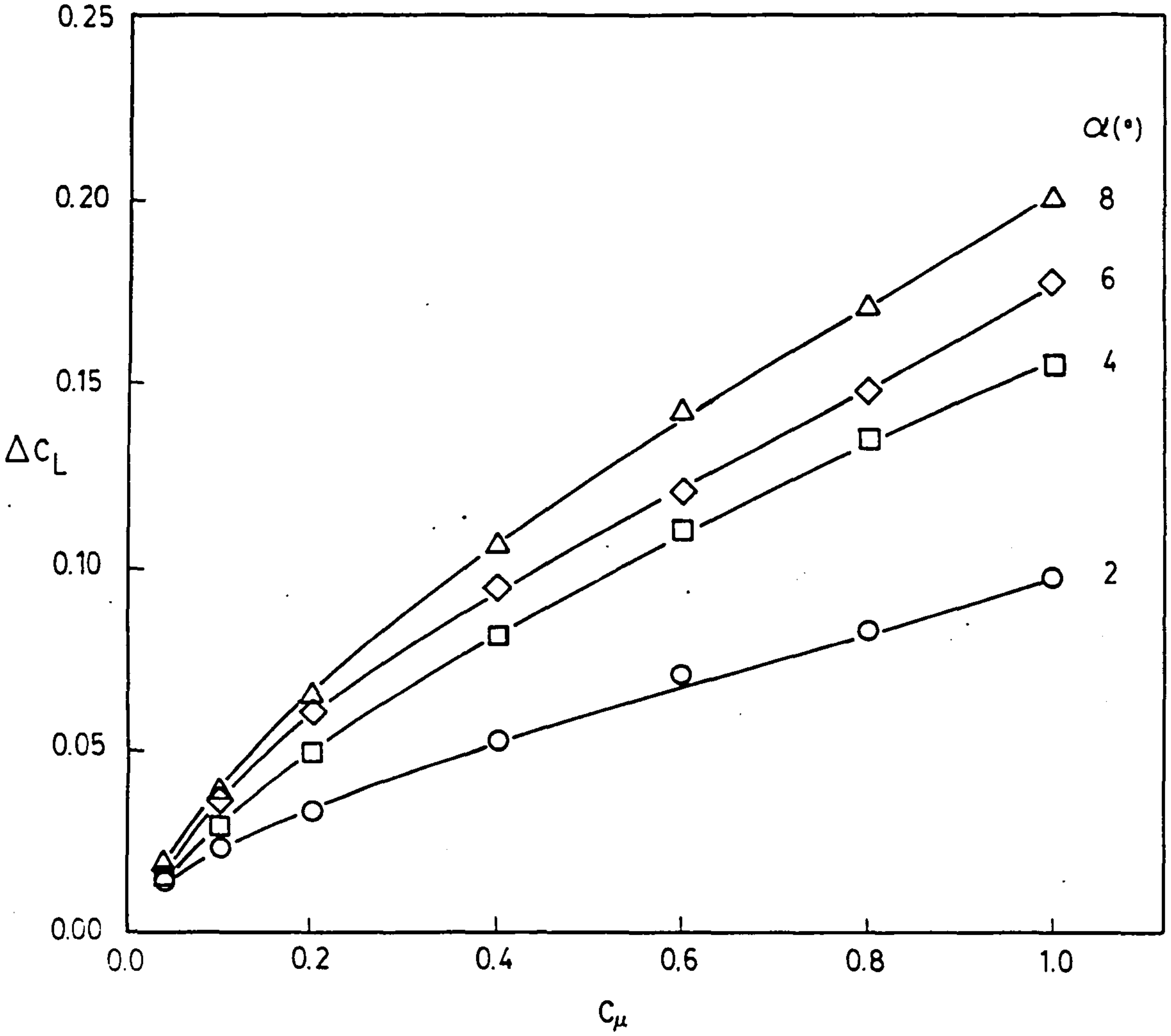

Fig. 14 Lift increment as function of blowing intensity.

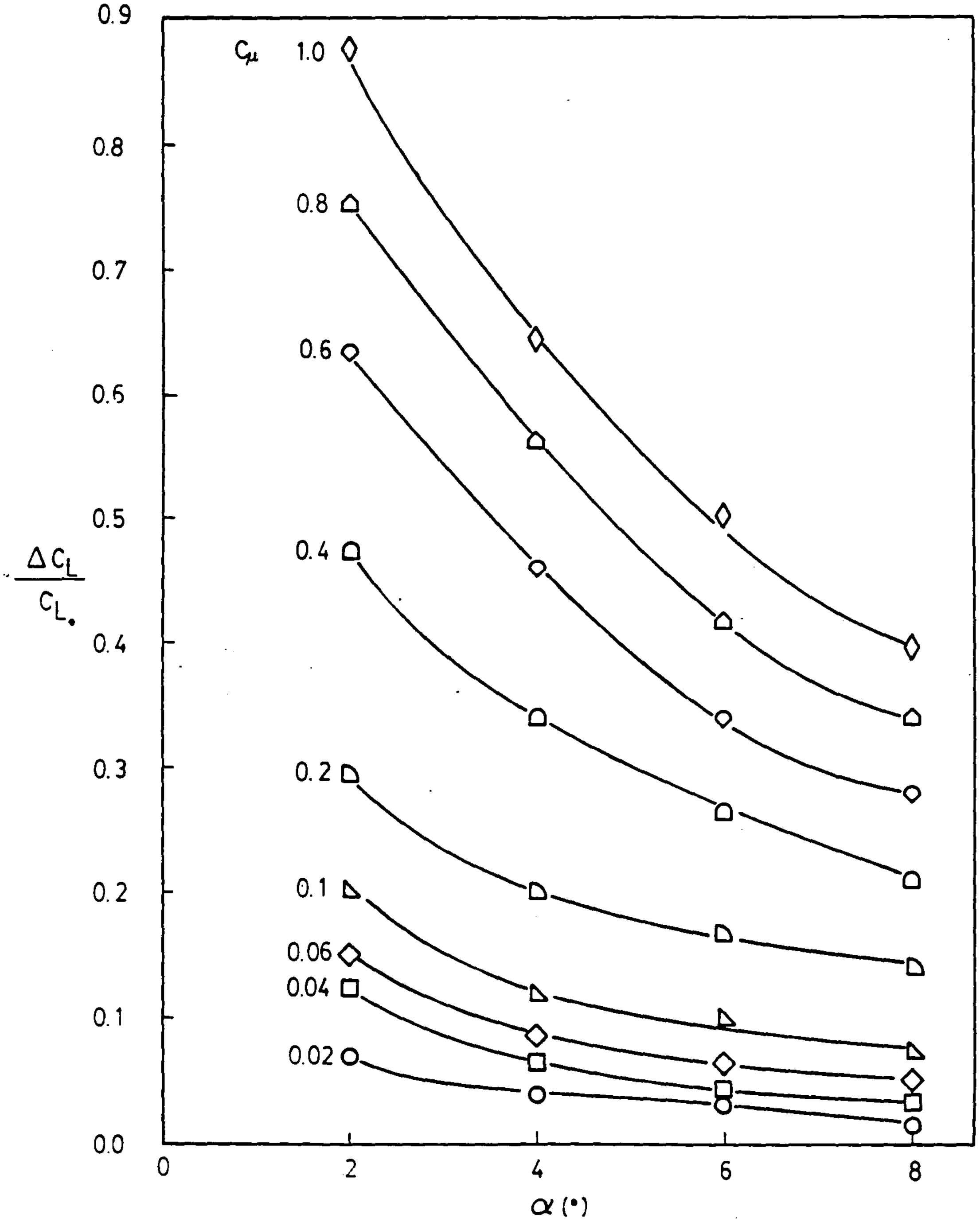

Fig. 15 Relative lift increment as function of angle of attack.

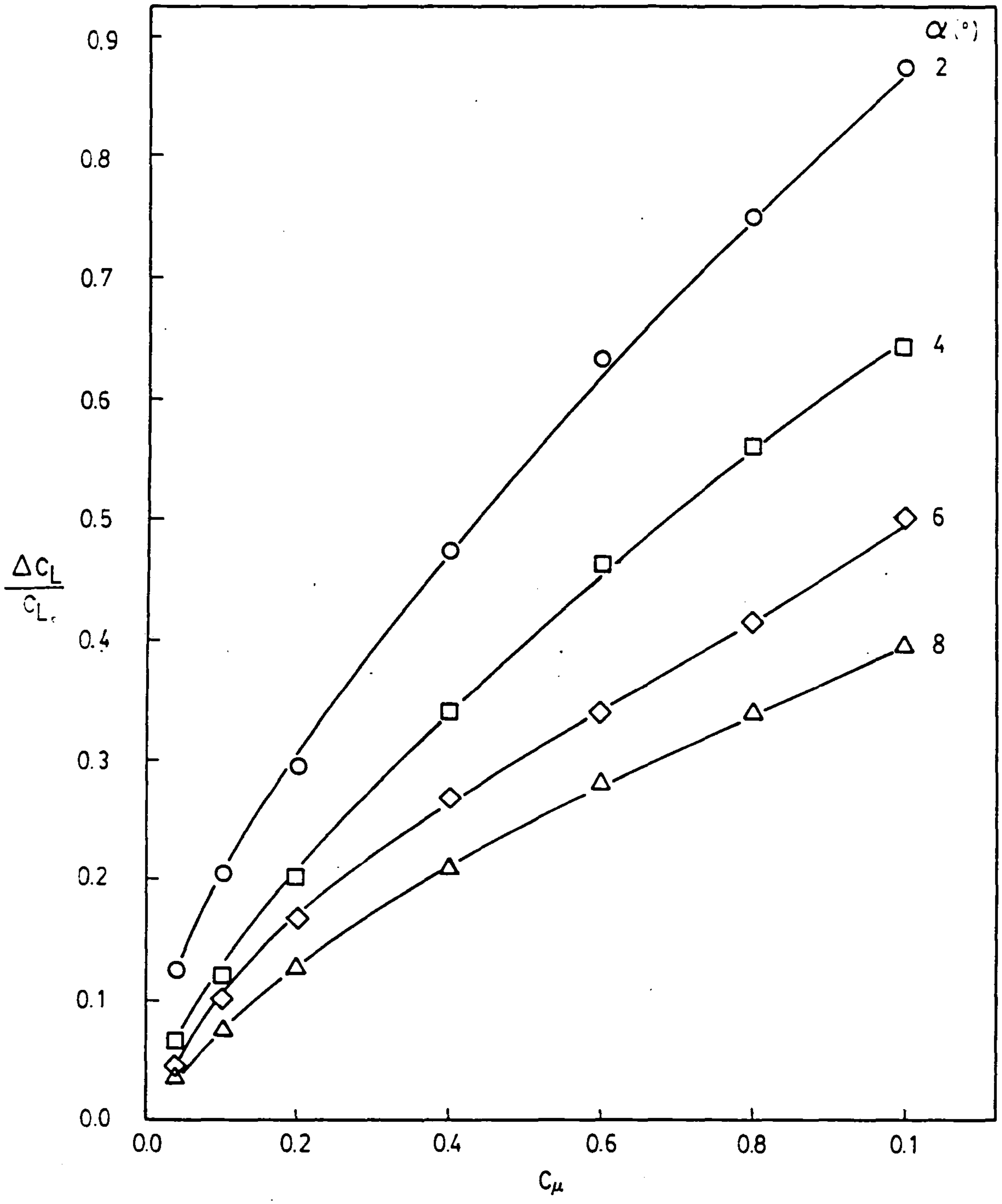

Fig. 16 Relative lift increment as function of blowing intensity.

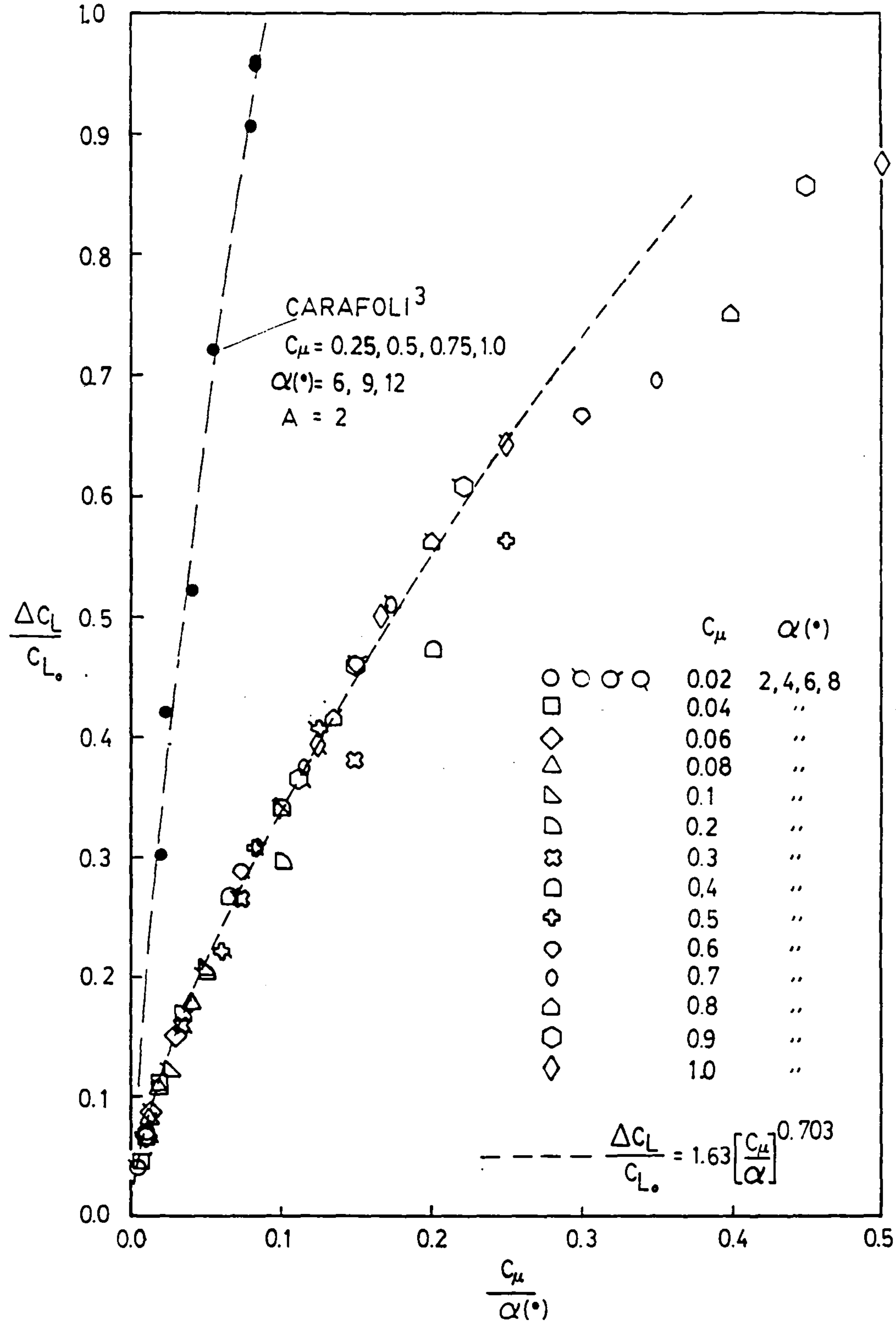

Fig. 17 Collapse of relative lift increment data.

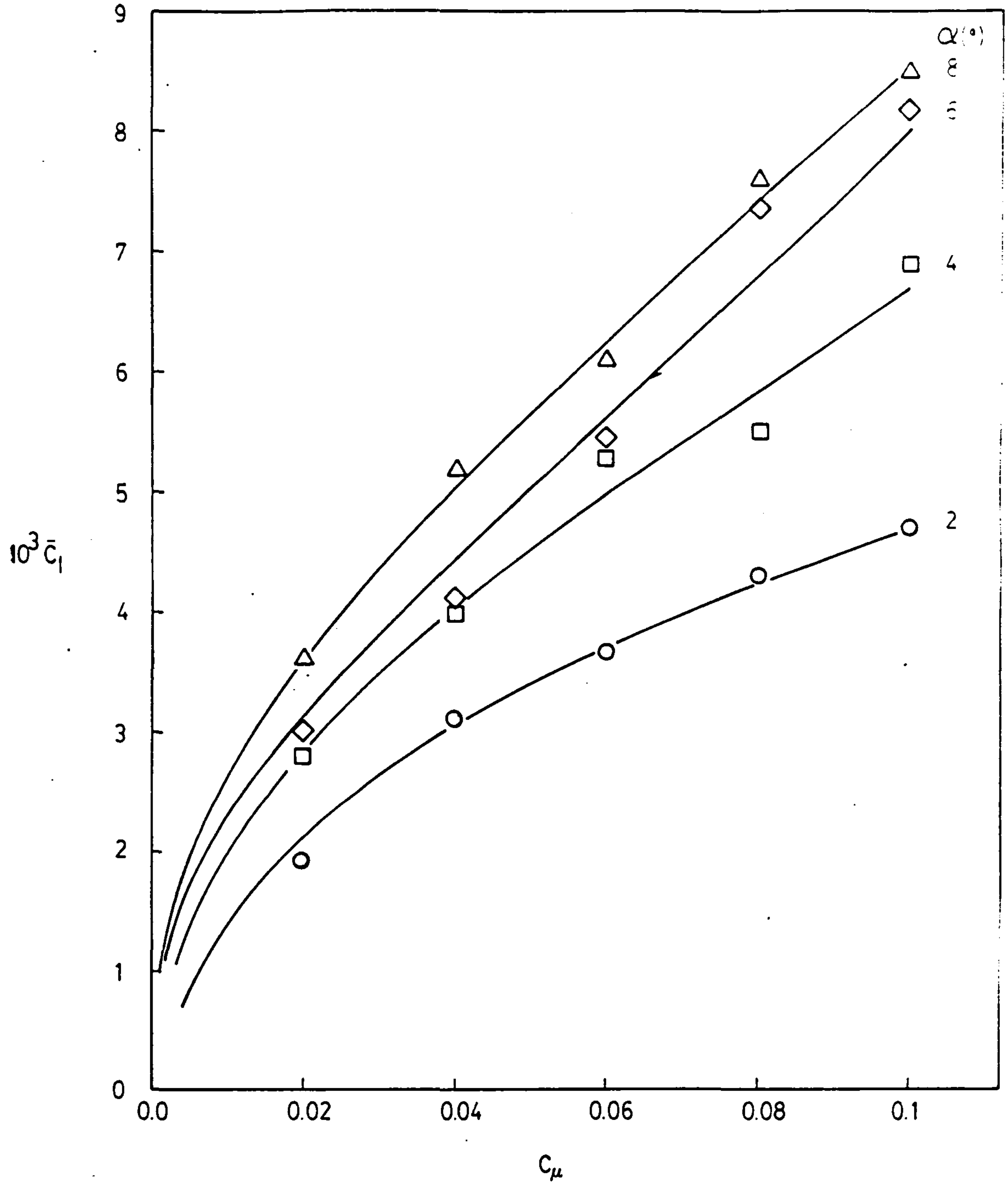

Fig. 18 Measure of rolling moment coefficient.

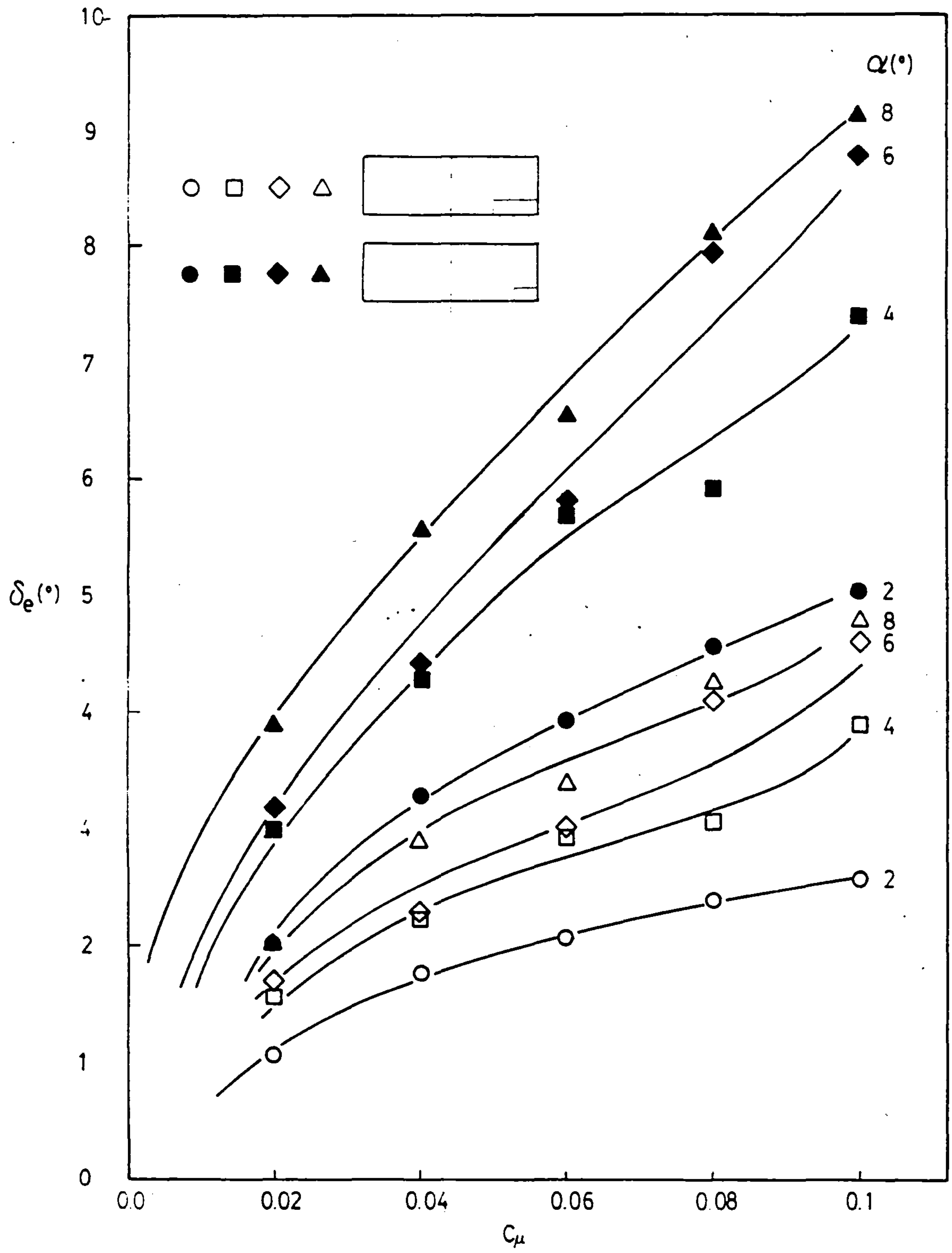

Fig. 19 Equivalent aileron deflexion angle.

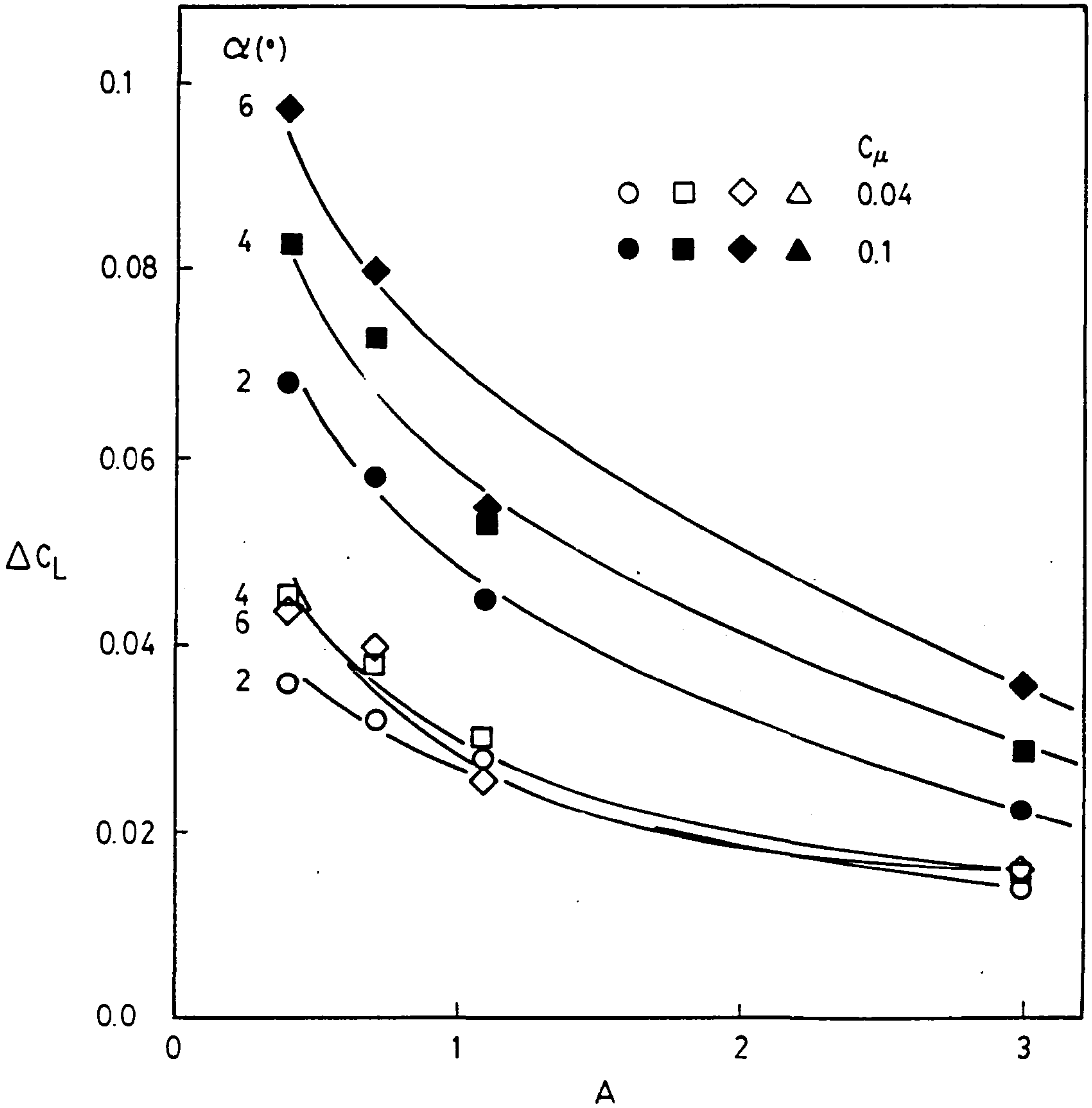

Fig. 20 Effect of wing aspect ratio on lift increment.

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